The origin of Pluto's peculiar orbit

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THE origin of Pluto's unusual orbit—the most eccentric and inclined of all the planets—remains a mystery. The orbits of Pluto and Neptune overlap, but close approaches of these two planets are prevented by the existence of a resonance condition[1]: Pluto's orbital period is exactly 3/2 that of Neptune, which ensures that the conjunctions always occur near Pluto's aphelion. Long-term orbit integrations[2-5] have uncovered other subtle resonances and near-resonances, and indicate that Pluto's orbit is chaotic yet remains macroscopically stable over billion-year timescales. A suggestion[4] that the orbit may have evolved purely by chaotic dynamics appears unlikely in light of recent orbital stability studies[6], unless one appeals to a well-timed collision to place Pluto in its stable orbit[19]. Here I show that Pluto could have acquired its current orbit during the late stages of planetary accretion, when the jovian planets underwent significant orbital migration as a result of encounters with residual planetesimals[7]. As Neptune moved outwards, a small body like Pluto in an initially circular orbit could have been captured into the 3:2 resonance, following which its orbital eccentricity would rise rapidly to its current Neptune-crossing value.

Consider a mass m_c of planetesimals ejected to Solar System escape orbits by a planet of mass M at orbital radius r. From conservation of angular momentum, it follows that the planet suffers a decrease of orbital angular momentum and a concomitant decrease of orbital radius given by

$$\delta r/r \approx -2(\sqrt{2}-1)m_c/M \qquad (1)$$

For planetesimals that are scattered outwards away from the Solar System but do not achieve escape orbits (remaining bound in the Oort cloud of comets which exists as a halo surrounding our planetary system at distances greater than 20,000 astronomical units (AU)), the numerical factor in equation (1) would be slightly smaller. Conversely, planetesimals scattered into the inner Solar System increase the orbital radius and angular momentum of the planet. The four jovian planets acting together, however, behave counter to this simple picture. Consider planetesimal scattering by Neptune: those planetesimals scattered outwards end up in the Oort cloud, or return to be re-scattered. A fraction of the latter set is scattered inwards. The inwardly scattered planetesimals are systematically ejected from the planetary system by the more massive Jupiter. Thus the outer, less massive planets, Neptune and Uranus, transfer control of the ejection process to the inner, more massive Jupiter and Saturn. (Note that Pluto's small mass—only two-thousandths of the Earth's mass—makes it an ineffective scatterer of planetesimals.) Numerical simulations of this process show that Neptune, Uranus and Saturn suffer a net gain of angular momentum while Jupiter suffers a net loss[7].

The timescale and extent of the radial migration of the planets is determined by the details of the late stages of the planet formation process and is poorly constrained by current theories. The mass of the Oort cloud, which is believed to have been populated by small bodies ejected from the zones of the jovian planets, is estimated to be $\sim 10\,M_\oplus$ ($M_\oplus$ = mass of the Earth) (ref. 8). The ejection of such a mass of planetesimals corresponds to an inward migration of Jupiter of a few tenths of an AU, and an outward migration of Neptune of several AU. In the final stages of planet formation, ejection and accretion of planetesimals will occur concurrently; therefore, the timescale for the radial migration of the planets is expected to be comparable to that of accretion. An approximate lower limit for the latter is the observed $\sim 10^7$ yr lifetime of dust in disks around pre-main-sequence stars[9].

One consequence of Neptune's orbital expansion is that its orbital resonances would have swept across a range of heliocentric distances comparable to its radial migration. During this resonance sweeping, a small body such as Pluto, initially in a nearly circular orbit beyond Neptune, would have a significant probability of being captured into a resonance. Resonant perturbations from Neptune would transfer sufficient angular momentum to the body to keep it trapped in the resonance and to expand its orbit in concert with Neptune. A by-product of such a resonance capture is that Pluto's orbital eccentricity would have been excited to a high value. This may be seen by considering the perturbation equations in the restricted three-body approximation[10]. Near a $j:j+1$ resonance (where j is an integer), the resonant perturbations from Neptune on Pluto's orbital frequency, n_P, and eccentricity, e_P, are described by the following equations:

$$\dot{n}_P = 3(j+1)\mu_N \dot{n}_P^2 e_P f(\alpha)\sin\phi$$
$$\dot{e}_P = -\mu_N n_P f(\alpha)\sin\phi \qquad (2)$$

where the 'resonance angle' is defined by

$$\phi = (j+1)\lambda_P - j\lambda_N - \bar{\omega}_P \qquad (3)$$

λ denotes the mean longitude, $\bar{\omega}$ is the longitude of perihelion, μ_N is the mass of Neptune relative to the Sun, $\alpha = a_N/a_P < 1$ is the ratio of the semimajor axes of Neptune and Pluto, and $f(\alpha)$ is a positive function, with numerical value 2.48 at the 3:2 resonance. Let $\langle \dot{n}_N \rangle$ be the mean rate of change of Neptune's orbital frequency as its orbit expands. Upon capture into resonance, the orbital frequency of Pluto becomes locked to that of Neptune, that is

$$(j+1)\langle \dot{n}_P \rangle \approx j\langle \dot{n}_N \rangle \qquad (4)$$

It then follows from equations (2) and (4) that

$$\left\langle \frac{de_P^2}{dt} \right\rangle \approx -\frac{2}{3(j+1)}\left\langle \frac{\dot{n}_N}{n_N} \right\rangle = \frac{1}{(j+1)}\left\langle \frac{\dot{a}_N}{a_N} \right\rangle \qquad (5)$$

where the last expression follows from the keplerian relation between the orbital frequency and the semimajor axis ($n^2 a^3 = constant$). In other words, upon capture into resonance, Pluto's eccentricity would increase at a rate determined by the average rate of expansion of Neptune's orbit. Equation (5) can be integrated to yield

$$e_{P,final}^2 - e_{P,initial}^2 \approx \frac{1}{j+1}\ln\left(\frac{a_{N,final}}{a_{N,initial}}\right) \qquad (6)$$

Neptune's current semimajor axis is $a_{N,final} = 30.17$ AU. Thus, we deduce that in order to excite Pluto's eccentricity from near-zero to 0.25, $a_{N,initial} \approx 25$ AU is required at the time of Pluto's capture into the 3:2 Neptune resonance ($j=2$ in equation (6)); Pluto's initial orbital radius would have been 32.8 AU. Remarkably, this result is independent of the timescale (and other details) of the expansion of Neptune's orbit. But there exists a practical constraint on the orbit expansion timescale, namely that it be much

longer than the period of the resonant perturbations, in order that resonance capture be effected[11]. This lower limit on the orbit expansion timescale is $\sim 10^5$ yr.

The above analysis is based on first-order perturbation theory, and it is legitimate to question its validity, particularly in view of the fact that at the high eccentricity of 0.25, Pluto's orbit would become Neptune-crossing. Furthermore, the perturbations from the other jovian planets on Pluto (as well their mutual interactions) have been neglected in this analysis. In order to test the hypothesis more rigorously, we have carried out a numerical integration of the orbit evolution of the four jovian planets and Pluto. As Pluto's mass is several orders of magnitude smaller than the jovian planets, we treated it as a massless 'test particle'. The numerical method used was a modified version of the mixed-variable-symplectic method[12-14], which is a very fast integrator particularly suited to Solar System integrations.

I assumed a simple model for the time variation of the orbital semimajor axes of the outer planets:

$$a(t) = a_f - \Delta a e^{-t/\tau} \qquad (7)$$

where a_f is the value at the current epoch and τ is the orbit expansion timescale. I chose $\Delta a = 0$, 1, 3 and 6 AU for Jupiter, Saturn, Uranus and Neptune, respectively, consistent with the net migration induced by the ejection of a few $M_\oplus$ of planetesimals from the outer planetary region. This orbital migration was modelled in the equations of motion by means of a force of magnitude $f = f_0 e^{-t/\tau}$ on each planet along the direction of its velocity. (f_0 can be related in a straightforward manner to a_f, Δa and τ.) So that the simulation would use a reasonable amount of computer time, the total integration time was 20 Myr, and τ was chosen to be 1.5 Myr. The qualitative behaviour is expected to be insensitive to τ for $\tau \gtrsim 10^5$ yr, which ensures an approximate adiabatic condition for the evolution near the 3:2 Neptune resonance.) Twenty 'test particle' Plutos were integrated along with the planets. Their initial orbital elements were chosen randomly as follows: a in the range 32.5–33.5) AU (just outside the 3:2 Neptune resonance), e in the range 0.0–0.3, i in the range $0°–10°$, and the angles (mean longitude, longitude of perihelion and ascending node) in the range 0–2π.

A typical case of the evolution found in the simulations is shown in Fig. 1. Nineteen of the 20 test Plutos were captured in the 3:2 resonance and the evolution proceeded in a manner very similar to that predicted by the simple analysis. (The one test Pluto that did not follow this evolution was captured in a 4:3 resonance and eventually had a close encounter with Neptune.) The behaviour of Pluto's a and e varied very little amongst the 19 cases, but the inclination evolution was rather sensitive to the initial conditions. The behaviour of the resonance angle ϕ was very stable; the final amplitude of its oscillations was found to be distributed in the range $30°–100°$. (The observed value is $76°$; recent numerical integrations[15] show that the long-term stability of the resonance requires a value $< 80°$.) We conclude that the analytical argument above does capture the salient features of the dynamical evolution. The long-period variations, evident particularly in the inclination, are possibly due to a nearby inclination-type secular resonance[16]. Longer integrations are required to determine the range of behaviours possible for Pluto's inclination.

A few words about the evolution of the jovian planets are in order. Although the initial orbits of the planets were significantly different from their current orbits, the behaviour of the orbital eccentricities and inclinations found in the simulations was similar to that observed in the long time integrations of the current planetary configuration[3].

The scheme outlined here for the origin of Pluto's highly eccentric, Neptune-crossing orbit is quite robust in that the probability of capturing Pluto in the 3:2 Neptune resonance from an initially circular orbit is very high. However, there are a few
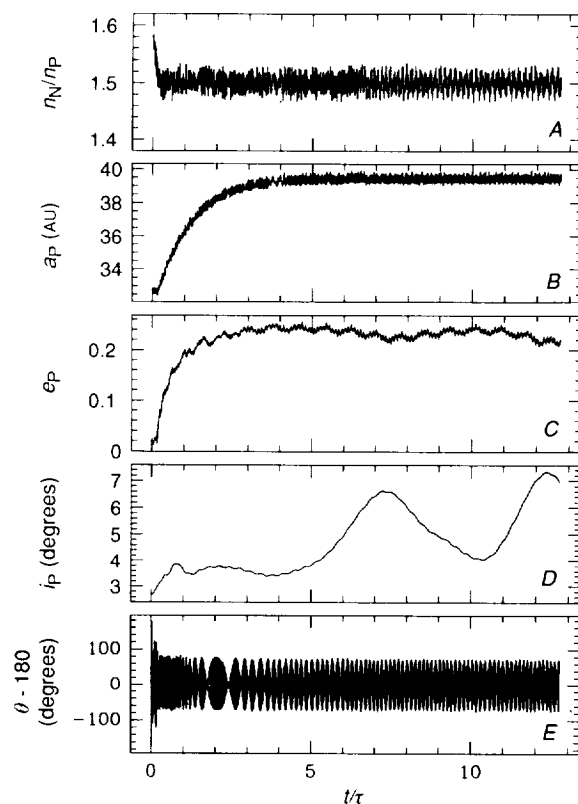

FIG. 1 The time evolution of Pluto's orbital elements is shown for a typical case of the capture of Pluto into the 3:2 Neptune resonance. (The time is indicated in units of τ, the characteristic timescale for the expansion of Neptune's orbit.) As Neptune's orbit evolves outward, the mean motion ratio (A) decreases initially until it reaches the value 3/2; at this point Pluto is captured in the resonance and subsequently its orbit also expands (B) in concert with Neptune. Pluto's eccentricity is pumped up rapidly (C) to a Neptune-crossing value. The evolution of the inclination (D) appears to be dominated by a nearby secular resonance, but remains to be understood. The resonance angle goes from circulations to remarkably constant-amplitude librations (E).

points of note. (1) I have modelled the radial migration of the jovian planets as a smooth process, whereas in reality it is stochastic. We expect that, as long as no single event produces too large a change in the planetary orbits, the smooth approximation should work well. A rough estimate for the mass of an ejected planetesimal that would invalidate this assumption can be obtained by equating the change in the orbital radius, $|\delta r/r|$ (Equation 1), with the half-width of the 3:2 Neptune resonance, $\delta a_P/a_P \approx 4(\mu_N f(\alpha) e_P/3)^{1/2}$ (ref. 11); this yields a mass $m_e \sim 10^{27}$ g, which is two orders of magnitude greater than the mass of Pluto. Thus, if we consider that Pluto was among the largest members of the planetesimal population beyond the orbit of Neptune surviving to the evolutionary stage considered here, then the smooth approximation appears quite reasonable. (2) In the numerical simulations, I assumed that the masses of the jovian planets were fixed at their current values during the entire evolution. The probability of resonance capture will depend upon the mass of Neptune. However, for sufficiently slow expansion of the planet orbits, resonance capture theory shows that the dependence on the mass of the perturbing planet is not very strong[11]. Therefore this limitation of the simulations is not likely to be of great import. (3) The analysis given here shows that the most direct requirement is on Neptune's orbital migration: $\Delta a_N \gtrsim 5$ AU. The sensitivity of the dynamics to the Δas of the other planets remains to be determined. The values chosen in

my simulation ensure that during their radial migration, the jovian planets do not encounter any strong orbital resonances amongst themselves, and therefore suffer only relatively small mutual perturbations. How restrictive this condition might be on the entire dynamical evolution described here requires further study. (4) Finally, the role of possible planetesimal collisions with Pluto during its evolution in the 3:2 Neptune resonance also needs to be evaluated. This may have an important bearing on the origin and properties of the Pluto-Charon binary.

The significant orbital evolution of the jovian planets implied by the model outlined here would have implications for a number of other problems concerning the outer Solar System, such as the capture of Triton by Neptune[17] and the structure of the putative Kuiper belt[18], as well as for studies of the evolution of the asteroid belt. □

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